The grain-size effects on scour around a cylinder due to tsunami run-up

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Abstract. The grain-size effects on scour around a vertical cylinder due to tsunami run-up were investigated experimentally using a large-scale laboratory facility. Sand and gravel were used as bed material around the cylinder. Temporal variations of scouring around the cylinder were optically observed with the multiple CCD cameras that were installed inside of the cylinder. All the other necessary data, e.g., water depth, flow velocity, and pore pressure, were obtained by the conventional electronic sensors. In addition, we measured the topography changes before and after the tsunami run-up. The temporal variations of the scour process were clarified. It was found that the replacement with the gravel near the cylinder reduced the scour area when the cylinder was at the shoreline or offshore, but was not always effective in reducing the maximum scour depth around the cylinder.

1. Introduction

It is well known that a tsunami attack causes substantial erosion and scour on the shore. For example, the 1960 Chilean tsunami scoured out the port entrance by more than 10 m at Kesen-numa Port in Japan. Recent tsunami surveys, from the 1992 Nicaragua tsunami to the 1998 Papua New Guinea tsunami, also discovered substantial tsunami scouring effects around structures and trees. In fact, scouring is sometimes the primary cause of structure damage and destruction.

It is likely that the tsunami-scour process around onshore structures is different from the present understanding of bridge-pier-type scour processes in river and coastal environments. Flows associated with tsunami run-up are far from being steady or uniform, and the scouring takes place over a short duration, often less than 15 min. It is also important to recognize that the onshore soil (sediments) conditions during tsunami run-up are initially unsaturated and suddenly become wet on the surface while the majority of pore spaces are still filled with air.

This complex problem must be approached experimentally to understand the physics and mechanisms of scour phenomena associated with tsunami run-up. Final scour depths were often measured by field observation well after tsunami attack; it is difficult to measure the scour depths in real time during tsunami run-up and drawdown on site. Scouring during tsunami run-

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Figure 1: The cylinder in the sediment tank. The gravel was placed in the black area near the cylinder.

up and drawdown can be larger than that after a tsunami attack because sand deposition in a temporary scour hole could occur during the end stage of the tsunami attack. For the design criteria for coastal structures, the maximum scour depth during the process is more important than the final scour depth.

The previous investigations of tsunami scouring processes are limited. Uda *et al.* (1987) found that scouring near a revetment due to tsunamis is governed by the topography behind the revetment. As for scouring in front of a revetment, Nishimura and Horikawa (1979) and Noguchi *et al.* (1997) found some correlation between the scour depth and the water depth in front of the revetment in the tsunami drawdown process. Kato *et al.* (2000) found that decrease in vertical effective stress in the sediments played an important role in scouring due to a tsunami attack on the shore.

Decrease in vertical effective stress is caused by a time lag between pore pressure variation in the soil and water pressure variation on the seabed. Pore pressure transmission depends on the permeability in the soil. The permeability is directly proportional to a square of grain size. For our study, we investigated the grain-size effects on tsunami-induced scour near the cylinder using the same experimental setup appointed by Kato *et al.* (2000).

Table 1: Experiment condition.

Case	Bed material	Overburden depth	Cylinder location
1	sand	0.37	shoreline
2	sand	0.49	shoreline
3	sand	0.20	shoreline
4	gravel	0.37	shoreline
5	gravel	0.20	shoreline
6	gravel	0.20	shoreline
7	sand	0.37	4m onshore
8	gravel	0.37	4m onshore
9	gravel	0.37	4m offshore
98 case 6	sand	0.37	4m offshore

2. Experiment Condition

A series of experiments was performed in a 135-m long, 2-m wide, 5-m deep sediment tank at Public Works Research Institute, Tsukuba, Japan. To generate a wide variety of long waves, the tank is equipped with the piston-type wave-maker driven by a large servo motor. The maximum stroke of the wave paddle is 2.4 m with the maximum speed of 1.11 m/s. It was tested and proven to generate a clean solitary wave of at least 40 cm high in a 3 m water depth. A beach of well-graded sediment (approximately $D_{50} = 0.35$ mm sand particles) was constructed with a uniform slope of 1/20. As shown in Fig. 1, the model cylinder was placed upright on the beach. The cylinder is 50 cm in diameter, made of 1 cm thick Plexiglas, water tight at the bottom end, and connected above to the aluminum cylinder in order to assure its stiffness. Because of the transparent cylinder wall, the scour process can be recorded from the interior with three miniature CCD video cameras, which cover a more than 180-degree view of the circumference from the upstream to the downstream sides.

Wave gages, an electromagnetic flow meter, and pore pressure transducers were placed as shown in Fig. 2. In addition, before and after each experiment, topography surveys were conducted in the 4-m by 1-m region around the cylinder. The sediment bed was carefully reconstructed in the uniform slope after each experiment run.

The experiments were performed for a total of 10 cases as listed in Table 1. A single incident wave condition was imposed for all cases; the ratio (a/h) of wave height a to the offshore water depth h is 0.09 for any cases. Since the position of the model cylinder is fixed throughout the experiments, the offshore water depths, h = 2.25 m, 2.45 m, and 2.65 m, correspond with the cylinder locations at 4 m onshore from the still shoreline, on the shoreline, and at 4 m offshore, respectively. Bed material within 25 cm off the cylinder wall and the bottom was replaced with gravel (approximately $D_{50} = 3.59$ mm) for cases 4, 5, 6, 8, and 9. The permeability coefficients are measured by the standard geotechnical testing and they are 0.05 cm/s for the sand and 4.43 cm/s for the gravel.

3. Topography Change Due to Tsunami Run-up

Before and after each experiment, a topography survey was conducted in the area of 1 m wide from the center of the cylinder toward the tank wall, 2 m onshore and 2 m offshore from the center of the cylinder. The measurement interval of 20 cm was used before the experiment, and, after the experiment, the finer interval of 5 cm was used within 50 cm from the cylinder, and a 10-cm interval in the rest of the surveyed area.

Figure 3 shows the beach-profile variations: a) in the cross-shore direction from the center of the cylinder and b) in the longshore direction from the cylinder. The horizontal axis indicates distance from the center of the cylinder normalized by the diameter of the cylinder. In the cross-shore direction, positive values indicate inshore and negative values indicate offshore. In the vertical axis, positive values indicate deposition and negative values indicate scour.

3.1 When the cylinder was on the shoreline

In cases 1, 2, and 3, with the sand of the seabed around the cylinder, scour occurred in the area of $x/B < 1.5$. On the other hand, in cases 4, 5, and 6, with the gravel of the seabed around the cylinder, scour depth was small even at the point of $x/B = 0.8$. It was found also in the longshore direction but not in the offshore direction that scour area in the cases of the gravel around the cylinder was slightly smaller than that in the cases of the sand around the cylinder.

3.2 When the cylinder was 4 m onshore from the shoreline

In the inshore side, scour did not occur in the area of $x/B > 0.8$, independent of grain size around the cylinder. In the offshore side, deposition was larger in the case of the sand around the cylinder. In the longshore side, scour depth was larger in the cases of the gravel around the cylinder. However, the differences between the cases of the sand and the gravel are small. Also note that they formed no scour hole around the inshore side of the cylinder, unlike the scour patterns found for other cylinder positions.

3.3 When the cylinder was 4 m offshore from the shoreline

In the onshore side, scour occurred in the area of $x/B < 1.0$ in the cases of the sand around the cylinder, but not even at the point of $x/B = 0.8$ in the cases of the gravel. In the offshore side, deposition occurred in both cases, and deposition was larger in the cases of the gravel. In the longshore side, scour occurred in the area of $y/B < 1.0$ in both cases, and scour depth was smaller in the cases of the gravel.

These results indicate that scour area was reduced by replacement with gravel around the cylinder when the cylinder was on the shoreline or 4 m offshore from the shoreline.

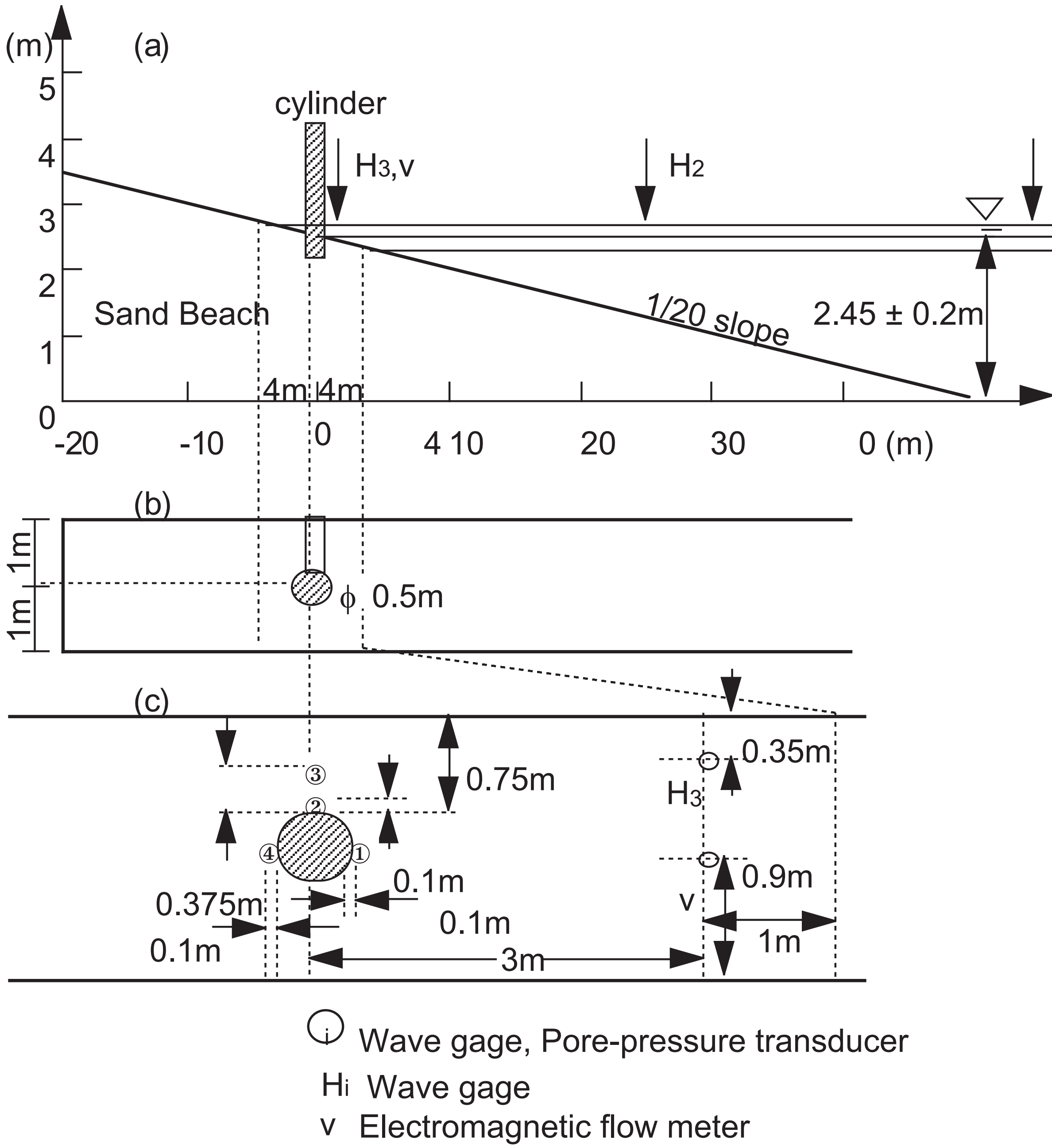

Figure 2: Schematic views of the experimental setup.

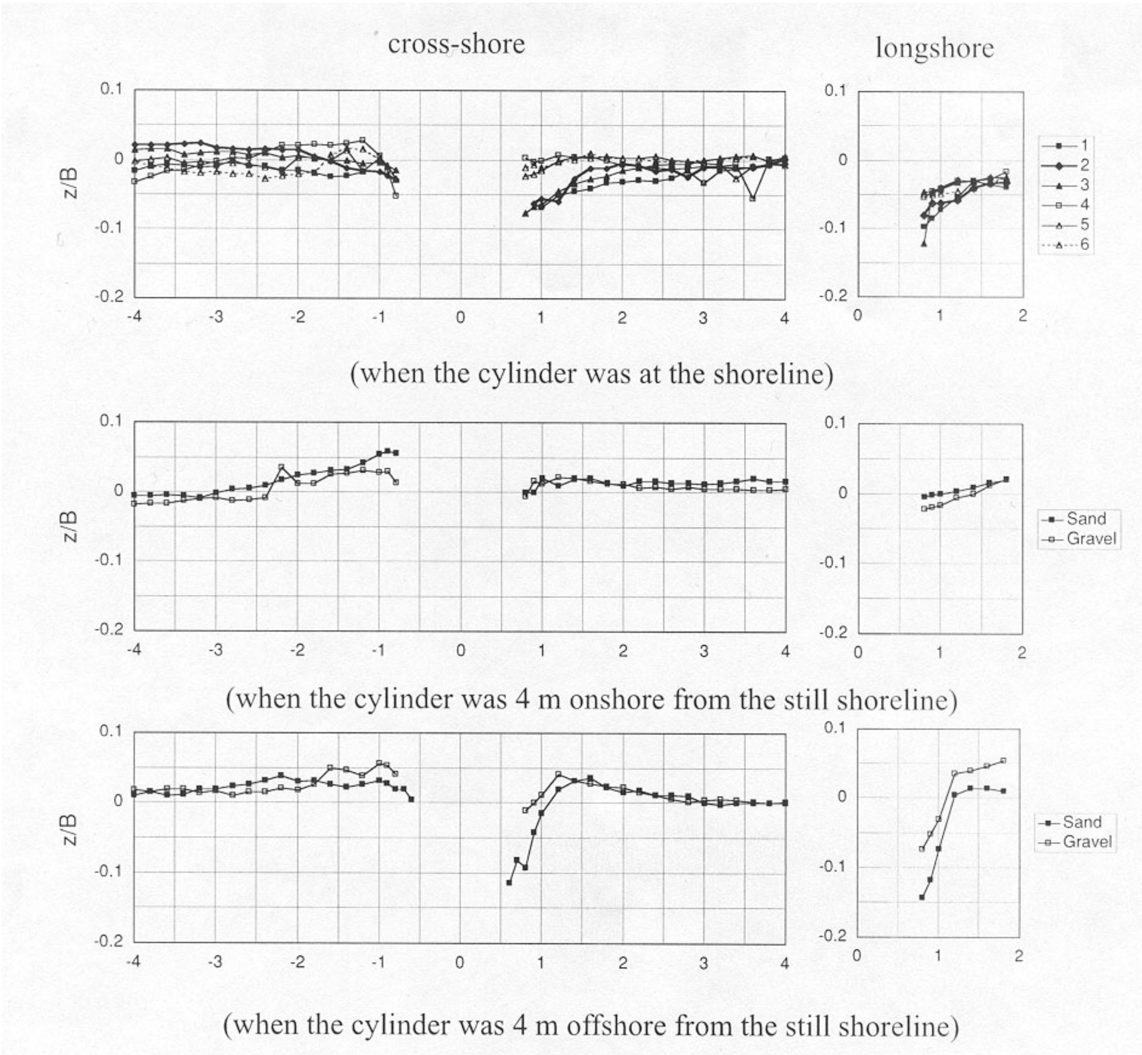

Figure 3: Beach profile variations.

4. Scouring Around a Cylinder Elucidated by Video Analysis

Figures 4 to 9 show maximum scour depths during tsunami run-up and final scour depth around the cylinder evaluated with video images taken by miniature CCD cameras installed inside of the cylinder. The scour depths were normalized by the diameter of the cylinder. In the vertical axis of the figures, positive values indicate deposition and negative values indicate scour. Differences between the maximum scour depth and the final scour depth are equivalent to filling of scour holes after the maximum scour.

4.1 Scouring at the offshore point

Figure 4 shows the maximum scour depth and the final scour depth when the overburden depth of the cylinder was 0.37 m. In the cases of both the sand and the gravel around the cylinder, the scour depths were largest when the cylinder was on the shoreline. The maximum scour depths were almost the same between the cases of the sand and the gravel when the cylinder was on the shoreline. Filling of the scour hole after maximum scour was greater in the cases of the sand when the cylinder was on the shoreline or 4 m onshore from the shoreline. Scour was little when the cylinder was 4 m offshore from the shoreline.

Figure 5 shows the relation between the overburden depth of the cylinder and the scour depth when the cylinder was on the shoreline. In the cases of both the sand and the gravel around the cylinder, the maximum scour depth increased with the overburden depth.

4.2 Scouring at the longshore point

Figure 6 shows the maximum scour depth and the final scour depth when the overburden depth of the cylinder was 0.37 m. In the cases of both the sand and the gravel around the cylinder, the maximum scour depth was large when the cylinder was on the shoreline or 4 m offshore from the shoreline. When the cylinder was on the shoreline, the maximum scour depth was almost equivalent between the cases of the sand and the gravel, but the final scour depth was smaller in the cases of the gravel around the cylinder than those in the cases of the sand. When the cylinder was 4 m onshore from the shoreline, the maximum scour was greater in the cases of the gravel around the cylinder. When the cylinder was on the shoreline from the shoreline, filling of the scour hole was larger in the cases of the gravel around the cylinder, different from that at the offshore point. When the cylinder was 4 m offshore from the shoreline, the final scour depth was almost equivalent between the cases of the sand and the gravel, but the maximum scour depth was slightly smaller in the cases of the gravel around the cylinder than that in the cases of the sand.

Figure 7 shows the relation between the overburden depth of the cylinder and the scour depth when the cylinder was on the shoreline. The tendency that the maximum scour depth increased with the overburden depth was found in the cases of the sand but not in the cases of the gravel.

4.3 Scouring at the inshore point

Figure 8 shows the maximum scour depth and the final scour depth when the overburden depth of the cylinder was 0.37 m. In the cases of both the sand and the gravel around the cylinder, the maximum scour depth was large when the cylinder was on the shoreline or 4 m offshore from the shoreline. Similar to the longshore point as shown in Fig. 6, when the cylinder was on the shoreline, the maximum scour depth was almost the same between the cases of the sand and the gravel, but the final scour depth was smaller in the cases of the gravel around the cylinder than that in the cases of the sand.

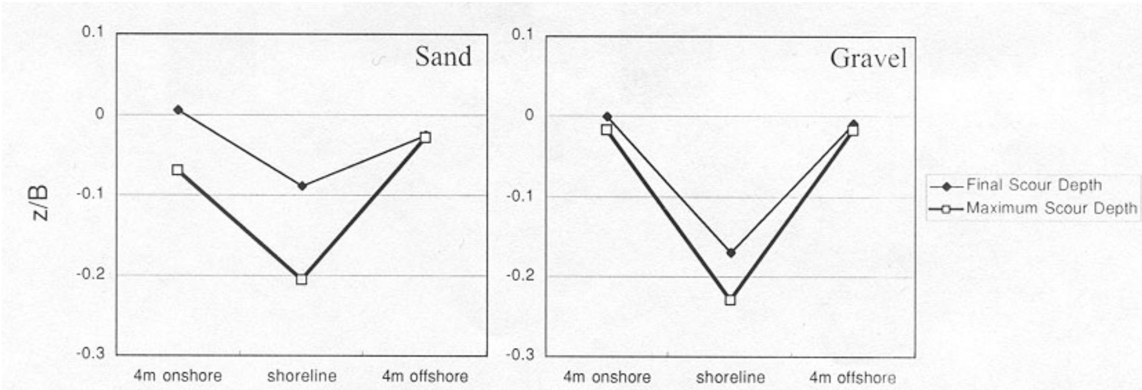

Figure 4: Scour depth at the offshore side where the overburden depth was 0.37 m.

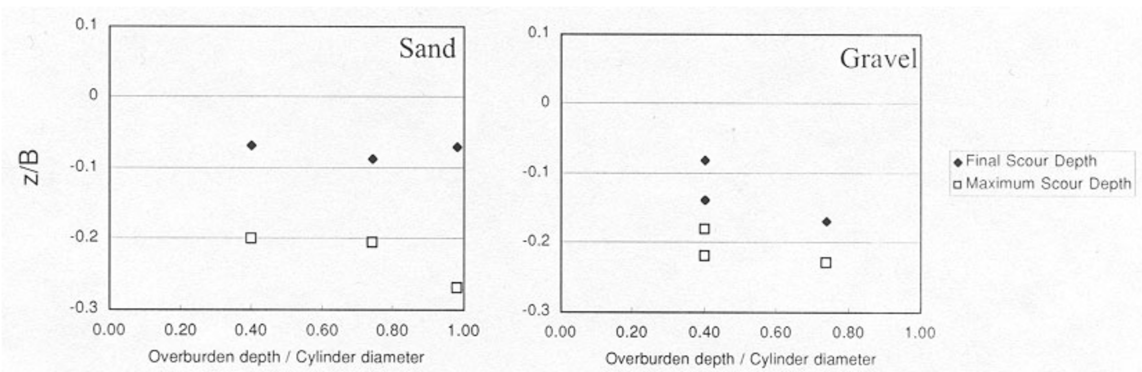

Figure 5: Scour depth at the offshore side where the cylinder was at the shoreline.

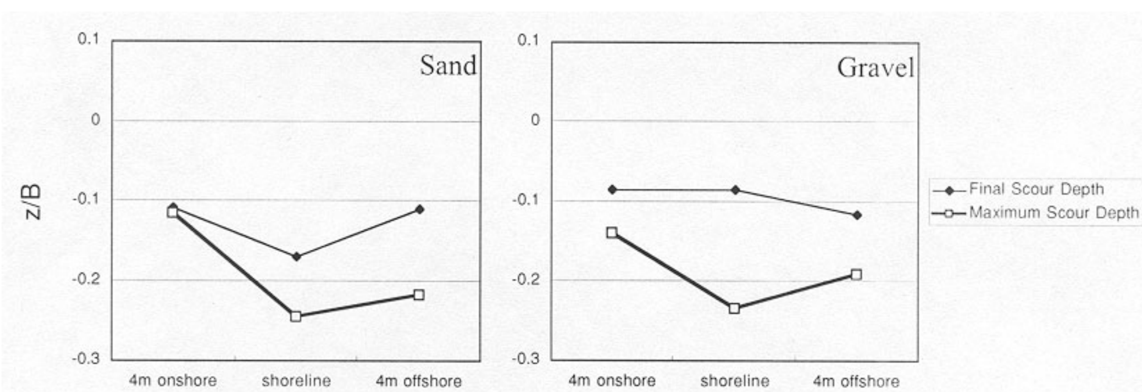

Figure 6: Scour depth at the longshore side where the overburden depth was 0.37 m.

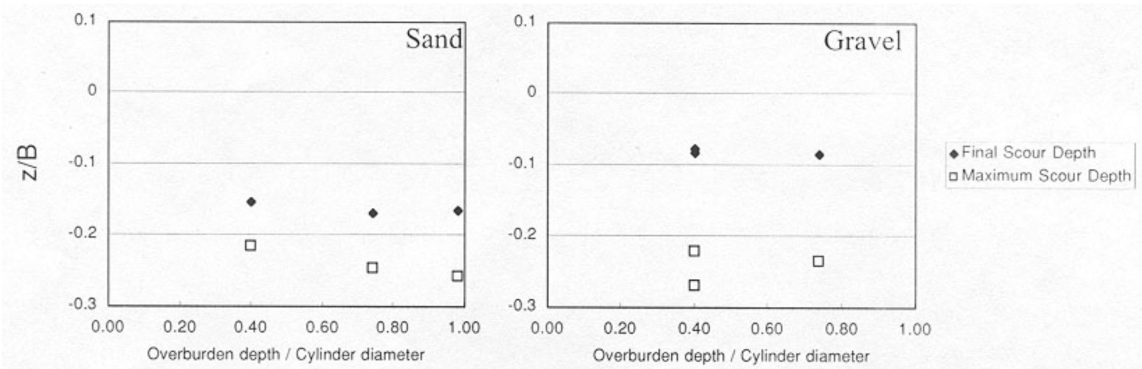

Figure 7: Scour depth at the longshore side where the cylinder was at the shoreline.

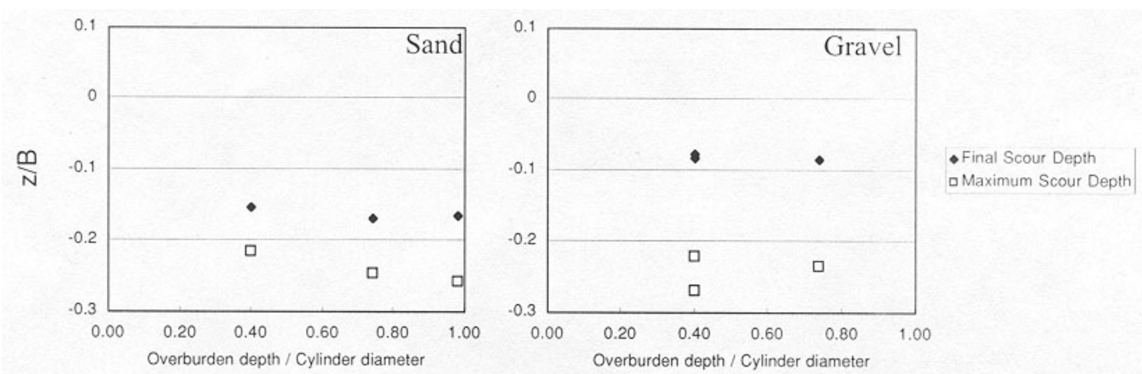

Figure 8: Scour depth at the inshore side where the overburden depth was 0.37 m.

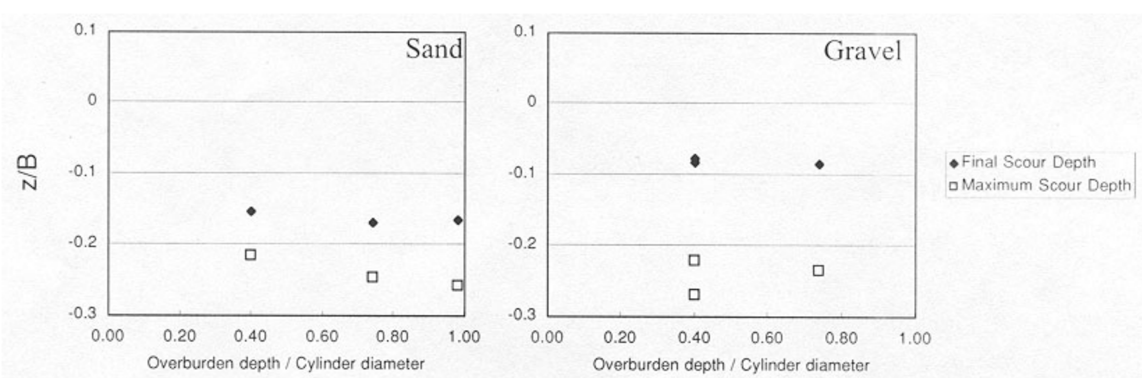

Figure 9: Scour depth at the inshore side where the cylinder was at the shoreline.

Table 2: Effect of replacement with gravel on scour mitigation.

	Cylinder location		
Side	**4 m onshore**	**Shoreline**	**4 m offshore**
offshore	positive	little	little
longshore	little	little	little
inshore	little	little	negative

When the cylinder was 4 m onshore from the shoreline, the maximum scour was greater in the cases of the gravel, and filling of the scour hole was larger in the cases of the gravel around the cylinder as well as at the longshore point. When the cylinder was 4 m offshore from the shoreline, both the maximum scour depth and the final scour depth were larger in the cases of the gravel than those in the cases of the sand. This result is different from the offshore point or the longshore point.

Figure 9 shows the relation between the overburden depth of the cylinder and the scour depth when the cylinder was on the shoreline. The tendency of decrease in the maximum scour depth with the overburden depth was found in the cases of the sand. This trend is opposite to those at the offshore side and at the longshore side. No distinct effect of the overburden depth is found in the gravel.

5. Relation Between Wave Height and Scour Depth

Figure 10 shows the relation between wave heights and maximum scour depths when the cylinder was 4 m onshore from the shoreline, on the shoreline, and 4 m offshore from the shoreline. The wave heights a and the maximum scour depths z were normalized by the cylinder diameter B. The data included the results of the experiments by Kato *et al.* (2000) as well as those shown in Table 1.

At the offshore side, the maximum ratio of z/B to a/B was 0.62 when the cylinder was on the shoreline, 0.23 when the cylinder was onshore, and less than 0.1 when the cylinder was offshore. At the longshore side, the maximum ratio of z/B to a/B was about 0.6 when the cylinder was on the shoreline or offshore, and 0.35 when the cylinder was onshore. At the inshore side, the maximum ratio of z/B to a/B was about 0.6 when the cylinder was offshore or on the shoreline, and 0.24 when the cylinder was onshore. These results indicate that scour depth around the cylinder near the shoreline due to a tsunami is expected to be smaller than incident wave height for the design of coastal facilities.

6. Effect on Scour Mitigation

Table 2 shows the effects of replacement with the gravel on scour mitigation judged by Fig. 10. Except for the offshore point when the cylinder was 4

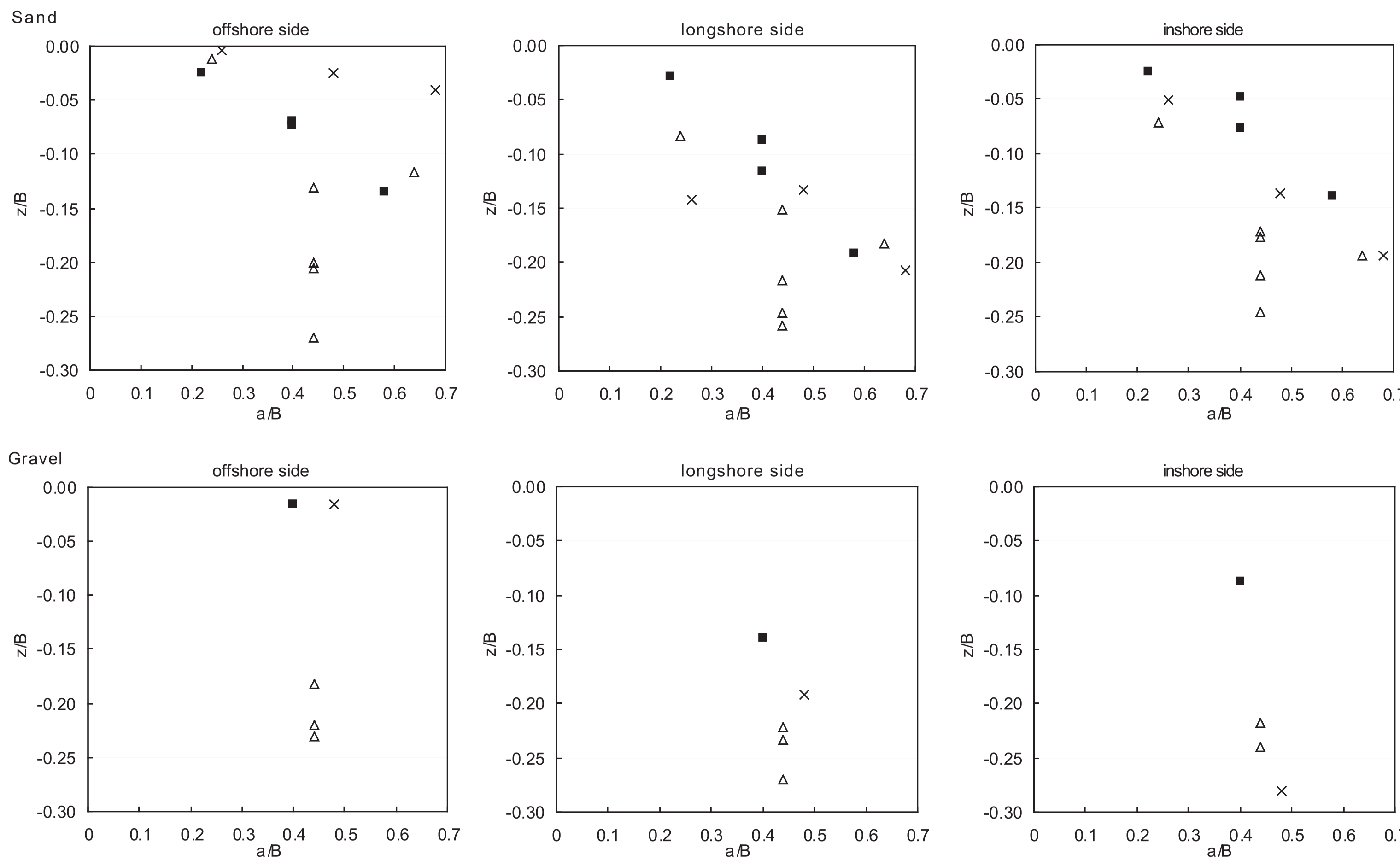

Figure 10: Relation between wave height and scour depth when the cylinder was 4 m onshore from the shoreline (■), on the shoreline (△), and 4 m offshore from the shoreline (×). Wave height a and scour depth z were normalized by the cylinder diameter B.

m onshore from the shoreline, the replacement of the gravel had little or negative effects on scour mitigation. Since flows during the tsunami run-up and drawdown process were fast, even the gravel around the cylinder could be carried away.

Table 3 shows effects of the overburden on scour mitigation when the cylinder was at the shoreline. The effects were evaluated with the maximum scour depth. The increase of the overburden had negative effects on scour mitigation at the offshore point and the longshore point, and positive effects at the inshore point in the cases of the sand around the cylinder. Such effects are not apparent for the cases of the gravel.

Table 3: Effect of overburden on scour mitigation when the cylinder was at the shoreline.

	Bed material	
Side	**Sand**	**Gravel**
offshore	negative	negative
longshore	negative	little
inshore	positive	little

7. Conclusions

The principal findings may be summarized as follows:

1. The scour area was reduced by the replacement of the sand with gravel around the cylinder when the cylinder was on the shoreline or offshore.

2. Scour depth around the cylinder near the shoreline could be expected to be smaller than incident wave height for the design of coastal facilities.

3. The flow due to the tsunami was fast enough to carry away the gravel on the bed, and in most cases the replacement with the gravel near the cylinder had little effect on the maximum scour depth; the gravel reduced the maximum depth of scour at the offshore side when the cylinder was onshore, but actually increased it at the inshore side when the cylinder was offshore. The use of gravel for scour mitigation is not supported by these initial results.

8. References

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